THE DEVELOPMENT OF A DIRECT TECHNIQUE FOR THE DETERMINATION OF TURBULENT FLUXES WITH AUTONOMOUS UNDERWATER VEHICLES

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LONG-TERM GOALS

Our long-term goal is to measure the horizontal variability of heat and salt flux in the upper ocean. This will allow us to study the turbulent boundary layer under non homogeneous forcing and the development of coherent boundary layer features such as rolls and Langmuir circulation.

OBJECTIVES

Our immediate objective is to develop a technique to measure vertical water velocity and the turbulent fluxes of heat and salt with Autonomous Underwater Vehicles (AUV), and to construct a vehicle to fully test and exploit the technique. We have done this in a limited way with our Autonomous Conductivity and Temperature Vehicle (Morison and McPhee, 1997). We use the vertical motion of the ACTV as a proxy for the vertical motion of the water through which it moves. Comparison with other measurement techniques indicates this produces reasonable estimates of flux at the scales of convective turbulence. The key elements of the new technique will be to use all available guidance and control data and account for the dynamics of the vehicle in the estimation of vertical velocity. A new small AUV will be built for proving the technique. The new AUV is crucial for this because it will have an adequate sensor suite to fully measure the vehicle motion and its configuration and control system will be optimally designed to determine vertical velocity.

APPROACH

The new technique for determining vertical velocity is based on Kalman filtering (Gelb, 1974). It satisfies the requirements of incorporating all possible sensor data and accounting for vehicle dynamics. The Kalman filter makes an estimate of the state of a dynamic system that is an optimal combination of the modeled response of the system and instantaneous measurements of the system state. The estimates are optimum in a weighted least square sense, with the weighting dependent on the estimated measurement error and forcing variance. The filter is recursive, i.e., the estimates depend only on present measurements and the estimate at a preceding time. As such, a filter only runs forward in time and can indeed be used in real time. The analysis of vehicle data can be done after all data are collected. In such a case the highest accuracy is obtained by running a Kalman filter forward and backward in time over the data in a process called Kalman smoothing.

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The first issue in developing the technique is deriving a system model. The second issue is estimating the measurement errors and the forcing variance. The derived model and error estimates are then used in the Kalman smoothing technique to estimate vertical water velocity. These can be combined with vehicle measurements of temperature and salinity to determine heat and salt fluxes.

A new Autonomous Micro-conductivity Temperature Vehicle (AMTV) is being developed to take full advantage of the new analysis technique. We will evaluate the turbulence estimation technique for several vehicle configurations, control systems and sensor suites. In this way we can develop an approach that is more easily transferred to other AUVs. We are assembling the new vehicle based on the Woods Hole Oceanographic Institution's REMotely operated Underwater measurement System (REMUS). Micro-conductivity and micro-temperature sensors will be added to improve heat and salt flux determination. To increase the vehicle state measurements available for the determination of vertical velocity, the AMTV will employ at least a solid-state pitch-rate sensor. This adds an important inertial measurement of the crucial pitch and depth motions. A sensitive pressure sensor will be employed to obtain measurements of the small vertical motions due to vertical currents. A three-axis accelerometer package will be used to resolve total acceleration.

WORK COMPLETED

The first issue in developing the Kalman smoothing technique is deriving a dynamic model for the AUV. We have first modeled the ACTV because existing ACTV data from the ONR sponsored Lead Experiment (LeadEx) can be compared with turbulence measurements made by Miles McPhee and others at LeadEx (Morison and McPhee, 1997). The chance to validate the basic form of the system model against actual data gathered under field conditions will be extremely valuable in developing the smoother. We have derived a fourth order dynamic model that can easily be adapted to other AUVs by substituting the appropriate vehicle dimensions and specifications. Following Nahon (1996) and others the equations of vertical motion and pitch have been expressed as a combination of the hydrodynamic characteristics the vehicle and the vehicle control system. The vehicle state vector consists of the deviation from the steady-state of vehicle vertical velocity, depth, pitch rate, and pitch angle. Determination of the coefficients of the model requires estimates of the hydrodynamic lift and moment coefficients. So far, to derive these we have relied on standard literature (ex. Hoerner and Borst, 1975) and work done on similar AUVs here at the Applied Physics Laboratory (APL). Our derivation of the forcing by vertical currents is original but it follows Etkin (1971). So far it considers the vehicle as a point and ignores the effects of vorticity and pressure gradients in the water.

Figure 1 illustrates the simulated response of the ACTV to vertical water motion. We drive the simulation with an actual record of measured vertical water velocity from a fixed sensor at Lead 3 of LeadEx during ACTV Run 4 (Morison and McPhee, 1997; McPhee, 1997). The simulated vehicle velocity illustrates for the first time why the vertical motion of the AUV can be used as a proxy for vertical water motion. The vehicle velocity is remarkably similar to the water velocity that acts on it.

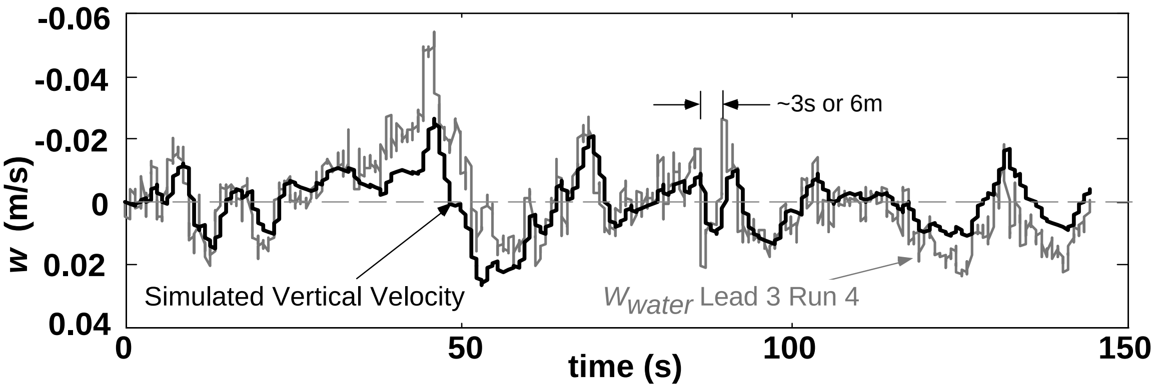

Figure 1. Simulated ACTV vertical velocity (positive down) in response to water vertical water velocity measured by McPhee (1997) at LeadEx Lead 3 during ACTV Run 4.

With the system model in hand we have developed the software to apply both Kalman filtering and smoothing. To test the software we have first applied it to simulated vehicle data after adding artificial noise to the modeled measurements. Figure 2 shows an example of applying Kalman filtering to the simulated vehicle motion of Figure 1. The only input to the filter is the simulated depth with an added 0.025 m rms white noise to represent sensor error. The actual water velocity and the estimated current are shown in Figure 3. The figure also shows the vertical vehicle velocity computed as the time-derivative of the noisy vehicle depth measurement. This is a worst case solution because only vehicle depth is used as a measurement and only forward filtering is performed. Nevertheless the velocity estimate reproduces the main features of the actual water velocity record. The Kalman filter accounts

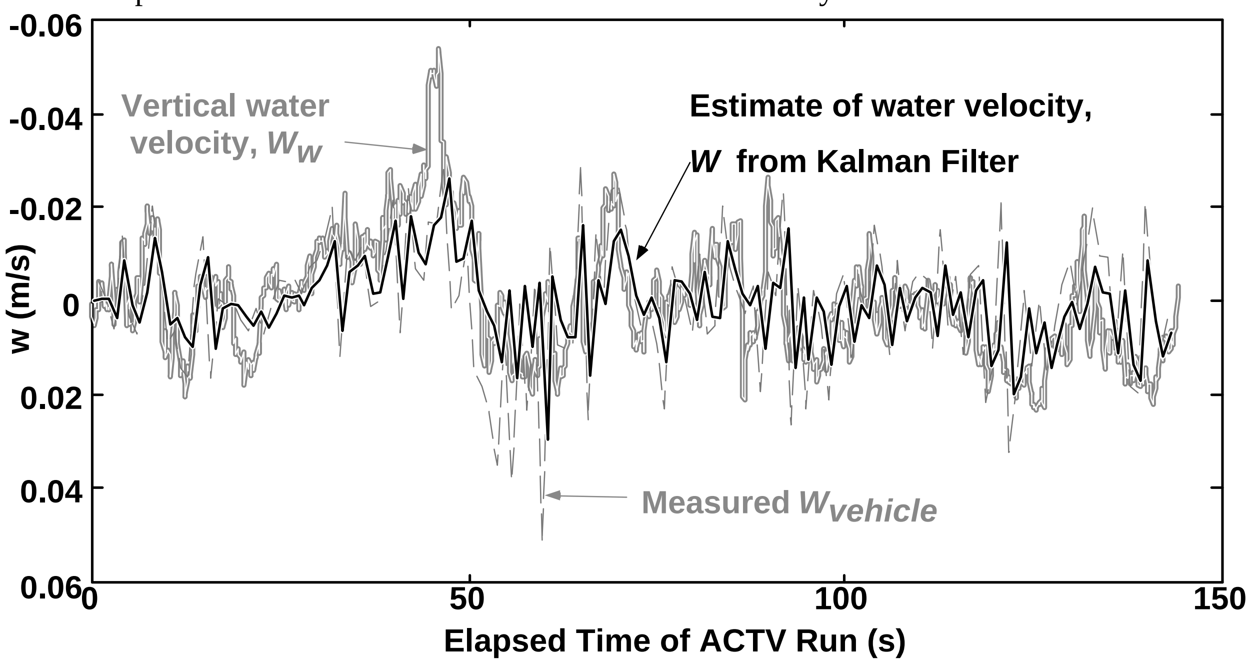

Figure 2. Simulated vertical of velocity of water, measured velocity of vehicle with measurement noise added, and vertical velocity of water estimated by Kalman filtering of measured depth. ACTV motion was simulated in response to the water vertical velocity as in Figure 1.

for the dynamics of the vehicle and significantly reduces noise in the water velocity estimate. Because a filter result is shown here, there is about a 2 second lag between the actual water velocity and the estimate. When the backward filtering is applied to result in a smoothed estimate, this lag is eliminated. Using the artificial data as above allows us to evaluate the Kalman smoother for an

essentially perfect vehicle model. This in turn allows us to evaluate the effect of different noise levels and the benefits of using more sensed state variables, such as pitch and pitch rate. We have also applied the Kalman smoother to actual ACTV data from LeadEx, and sample results will be shown in the next section.

We have also made good progress in constructing the new AMTV test vehicle. We have contracted with Chris Von Alt's group at WHOI to build a REMUS vehicle to be used as a basis for the AMTV. The vehicle has recently been delivered to APL. REMUS is very close to what we feel is the ideal size for the AMTV. It's standard length of 1.5 m is about the same as the ACTV but its diameter of 0.18 m is double the ACTV resulting in a displacement of 29 kg. This gives adequate capacity for added sensors and batteries. The short length is an advantage for the vehicle to respond to turbulence at the smaller of the energy-containing scales. Compared to the ACTV, the reduction in the ratio of surface area to volume is of some concern, because it may effect how well the AMTV responds to water motion. However, we can address this with added fixed control surfaces. This will be examined with simulations. Perhaps the most attractive feature of REMUS is the well-developed computer and control system. It uses a high level language (C++) which will allow us to tailor the control system parameters and data acquisition to our needs. We have begun to modify the REMUS to make the AMTV by adding specialized sensors. These include a Systron Donner Motion Pack accelerometer and angular rate sensor for precision determination of angular position and possible short term inertial motion sensing, a Paroscientific Digiquartz pressure sensor for precise measurement of vehicle depth, a Sea-Bird Electronics micro-conductivity and micro-temperature sensors for high frequency sampling of water temperature and salinity, and a Tritech precision altimeter to measure distance from the sea surface.

RESULTS

Figure 1 shows that the small AUV roughly follows the water velocity at the scales of ocean boundary layer turbulence and thus it illustrates why the simple approximations used to derive fluxes in Morison and McPhee (1997) work as well as they do. Going through the derivation of the model has given us insight into why the a small AUV follows the water. First, the AUV is neutrally buoyant. In this way it is essentially a motorized Lagrangian drifter (analogous to a blimp). The relative vertical water velocity is on average very small and only deviates momentarily when the AUV is moved into a new updraft or downdraft. Second, the typical AUV has near neutral stability in pitch or is slightly unstable. Our calculations suggest the ACTV for example has so much surface area forward of the center of gravity that when it encounters an updraft it has a tendency to pitch up and follow the updraft. Thus, such an AUV will tend to follow the updrafts and downdrafts with little relative vertical water velocity; the turbulence signal is in the motion of the AUV. This tendency helps to counter inertia-induced effects as the AUV first moves into an updraft or downdraft. Of course the AUV control system acts to return the vehicle to the commanded depth, but in the ACTV at least this control response is gradual enough so that any water velocity perturbations which act on the vehicle for less than about 20 seconds are not strongly countered by the control system. This tendency of the control system to counter the action of the vertical water velocity is seen in the velocity peaks centered around 50 seconds in Figure 1. In response to the upward velocity peak prior to 50 seconds the vehicle noses over and produces a slight downward bias in the vehicle velocity relative to the water. This persists until about 60 seconds into the run. Nevertheless, the ACTV velocity is similar to the water velocity during this large event. If we account for the horizontal velocity of the ACTV, the large event centered at 50 seconds has a wavelength of about 72 m and corresponds to the larger energy containing turbulent motions at LeadEx. The model also suggests the vehicle should respond well to motions with wavelengths at least as small as 5-6 m (see Figure 1 at about 80 s into the run).

Figure 3 illustrates the performance of the new Kalman smoother when applied to real data. It is

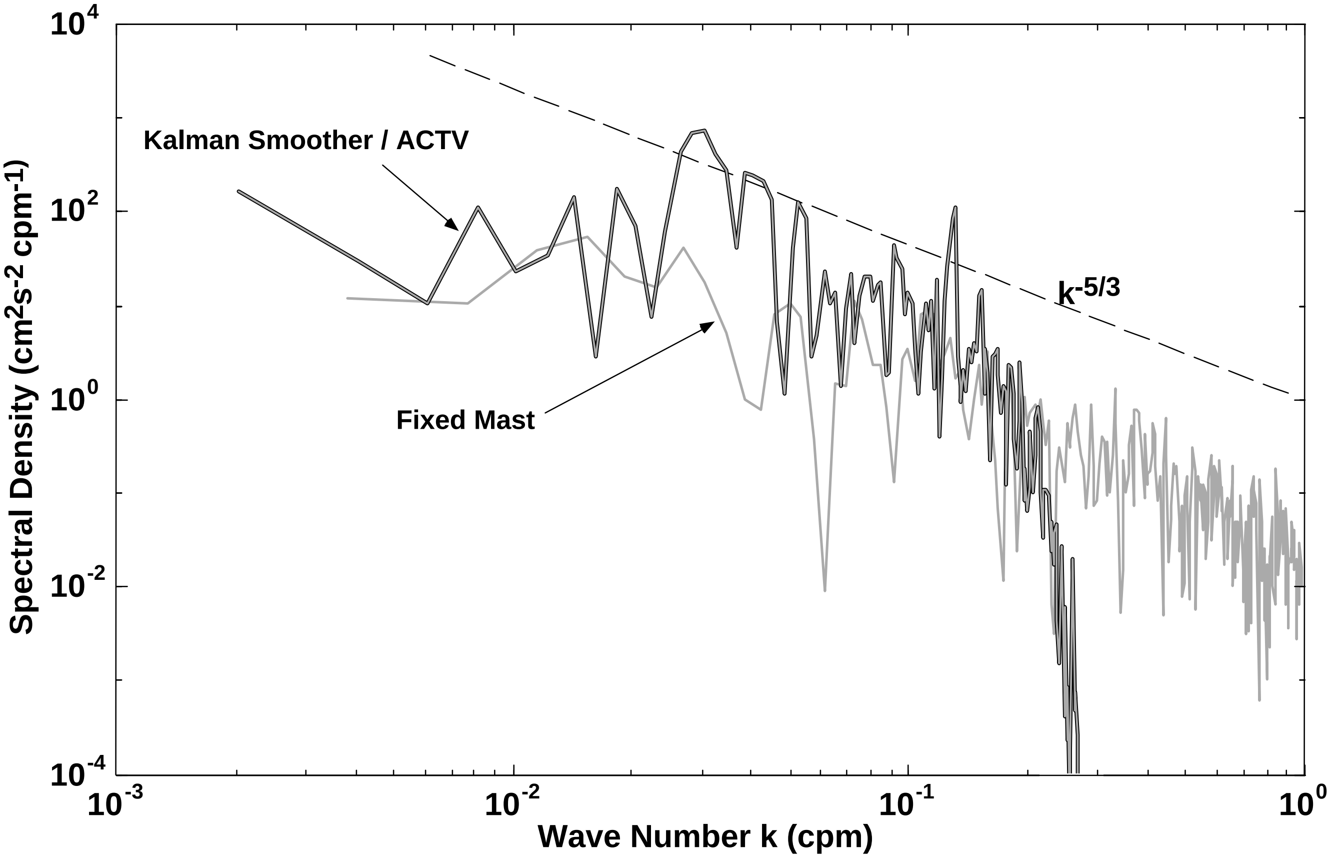

Figure 3. Spectrum of vertical velocity as estimated by Kalman smoother applied to the ACTV data of run 4 at lead 3 of LeadEx and spectrum of vertical velocity measured with the fixed mast sensor of Miles McPhee.

a comparison between the spectra of vertical velocity from the Kalman smoother applied to ACTV run 4 at lead 3 of LeadEx and vertical velocity as measured by fixed turbulence sensors at the time of the vehicle run. The two instruments are not sampling the identical water, but they were operated during this time in such a way that the statistics should be similar. In fact the spectra are quite similar. The Kalman spectrum cuts off near 0.2-0.3 cpm because we prefiltered the pressure data and perhaps because of the effects of averaging due to finite vehicle length. It is gratifying that the Kalman spectrum follows the direct measurement into the $k^{-5/3}$ inertial subrange. This is so even though all coefficients in the filter have so far been derived only from first principles. By examining comparisons such as this we hope to improve our vehicle models and smoother performance.

IMPACT / APPLICATIONS

The fundamental impact of this research will be to provide a technique whereby nearly any AUV can provide turbulence data as a side benefit to other sampling it carries out. This is because the proposed technique requires only data from a vehicle's on board motion sensors. Used with simple vehicles, the technique will yield spatial maps of turbulent energy. Used with sophisticated AUVs, the technique will also yield spatial maps of vertical fluxes of the other variables being measured. Such maps will be the key to identifying dynamically critical areas of the AOSN sampling regions and will be crucial to determining the budgets of heat, salt, biomass and pollutants.

TRANSITIONS

Vehicles like the AMTV and the analysis method we are developing could be used militarily. We visualize such AUVs making clandestine surveys of littoral areas. The method of extracting information on water motion from vehicle motion would have application in determining the wave energy in areas of planned amphibious assault. The technique may also find application as a non-acoustic detection and tracking tool. This would find application in "smart" and acoustically quiet weapons that could detect the wakes of vessels and follow them. Torpedoes using the technique in real time could conceivably follow turbulent ship wakes to their targets.

RELATED PROJECTS

As an outgrowth of this work and our ONR Arctic Mixed Layer work, we have been awarded an ONR grant under the BAA #AOSN program to test the new AMTV during the NSF-ONR sponsored program Surface HEat Budget of the Arctic Ocean (SHEBA). We will collaborate with Miles McPhee at SHEBA to intercompare vehicle turbulence measurements with his fixed point measurement. We have subcontracted with Chris Von Alt's vehicle program at WHOI to build the baseline AMTV vehicle. We have submitted a proposal to the AASERT Program to support the graduate student who has been working on the Kalman smoothing project in part with Applied Physics Laboratory funding.

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